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Standard Model Higgs searches at CDF

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Summary. — Fermilab Experiments CDF and D0 excluded in March, 2009 the existence of a Standard Model Higgs boson having a mass in the $[160; 170]\,\mathrm{GeV}/c^2$ range at 95% CL. We resume here the analysis channels and techniques used by CDF to reach this result.

PACS `14.80.Bn` – Standard-model Higgs bosons.

1. – Production and decay channels

In the Standard Model (SM), the Higgs process with the largest cross-section is $gg \to H$. The associated production of the Higgs with a W or Z boson (Higgs-strahlung) is about one order of magnitude less abundant. The Vector Boson Fusion (VBF) follows, occurring when the Higgs originates from the fusion of two intermediate bosons radiated from the two initial state quarks.

A common analysis choice for low-mass Higgs searches is to associate the $H \to b\bar{b}$ decay channel with a Higgs-strahlung production because in this way the lepton from the intermediate boson leptonic decay can be used as a trigger. The large missing transverse energy ($\not\!\!E_T$) from a Z decay can be used as well. If studying the $H \to WW$ process (high-mass Higgs) one can allow for all the production mechanisms, since the final state Ws will provide the convenient trigger objects.

2. – Analysis techniques

To deal with such challenging search/exclusion studies, it is necessary to both increase the signal acceptance and make the background rejection more efficient. To increase the acceptance, CDF uses dedicated triggers and applies lepton identification algorithms.

In the low-mass Higgs studies the distinction between heavy flavor jets (b-jets) and light jets is of particular interest in order to suppress the background. Jet flavor separators allow for a continuous b-tagging (Jet Probability JP and other neural network-based algorithms), while classical discrete b-taggers (SecVtx, an algorithm searching for secondary vertices inside the jet indicating a B hadron decay) return a tagged/non-tagged flag.

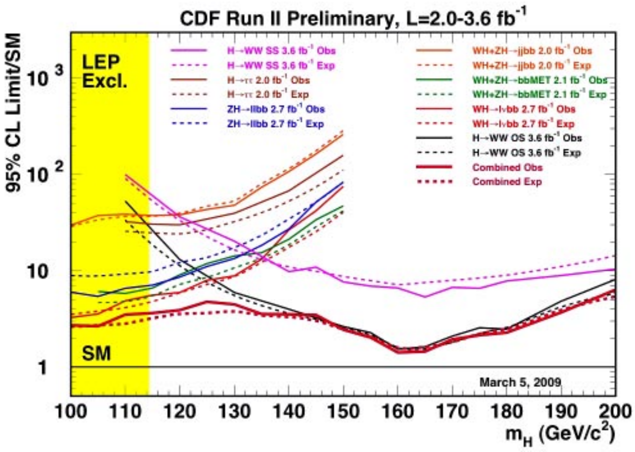

Fig. 1. – (Colour on-line) Dashed lines are the CDF limits on the Standard Model Higgs production cross-section as measured by the different analyses. The red solid line is their combination.

The distinction between signal and background is not always possible (irreducible background), but in the other cases is dealt with advanced multivariate techniques such as Neural Networks (NN), Martix Elements (ME), Boosted Decision Trees (BDT).

3. – Low-mass Higgs

We divide the analyses searching for a low-mass Higgs depending on the number of leptons (electrons, muons) in the final state.

3˙1. *No leptons*. – In this channel, $ZH \to \nu\nu bb$, no leptons are expected in the final state. The two neutrinos are signed by a large amount of missing energy $\not{E}_T$. Events like $WH \to (\ell)\nu bb$ are taken as well, when the lepton is not identified or escapes the detection. The trigger is given by a large $\not{E}_T$, indicating the two neutrinos, and by the presence of jets. Data and simulations are divided into b-tag categories: 2 SecVtx, 1 SecVtx+1 JP, or 1 SecVtx and one non-tagged jets. For each category the relevant background processes are studied and normalized to the real data. The main background contributions are given by QCD muti-jet production, W and Z with associated jets, top events and diboson production. Two NN are trained to separate the signals from the background processes, the first being used as a preselection by establishing a threshold cut. The second NN is trained once for each b-tag category and the resulting discriminants are eventually combined. A limit is set at 95% CL on the Higgs production cross-section which is given in units of the SM expected cross-section: 5.6 (observed: 6.9) at the Higgs mass of $115\,\mathrm{GeV}/c^2$ by using $2.1\,\mathrm{fb}^{-1}$ of CDF data, with lower limits for lower masses and higher limits for higher masses (see fig. 1).

3˙2. *One lepton*. – The process $WH \to \ell\nu bb$ is studied by two different analyses at CDF: by a combination of ME and BDT, and by using a NN. This channel is the most sensitive among the low-mass Higgs ones. The trigger searches for isolated electrons or muons in the central region, and also allows events with $\not{E}_T$ associated with jets if isolated tracks can be considered as misidentified leptons. The same three tagging categories as in the no-leptons channel are used here. The main discriminant is provided by the output from a BDT (making use of the event probability densities from ME) by one of the two analyses, and the output from a NN by the other. After processing $2.7\,\mathrm{fb}^{-1}$ of data, the limits set on the Higgs production cross-section, in units of the SM expected cross-section, is 5.2 (observed: 6.2) at the Higgs mass of $115\,\mathrm{GeV}/c^2$ from the ME + BDT, and 5.8 (observed: 5.2) by the NN one, at the same mass point. See fig. 1 for the complete set of limits provided.

The result from the two analyses is eventually combined with an evolutionary NN (called NEAT) and provides the limit of 4.8 (observed: 5.6) in the same units and for the same Higgs mass.

3·3. *Two leptons*. – As for the one-lepton case, the $ZH \to \ell\ell bb$ channel has two CDF analyses which are ME and 2D-NN. Events are triggered with a central electron or muon, then a second lepton is required in the event in addition to other fiducial cuts. The dominant background processes are Z bosons produced in association with jets, $t\bar{t}$ events and diboson production. The reconstructed two-lepton invariant mass is required to be compatible with the Z boson mass peak. Both the analyses use $2.7\,\mathrm{fb}^{-1}$ of data.

The first analysis uses probability density functions from ME and builds likelihood functions with it, then applies the Feldman-Cousins approach to set asymmetric limits. The result is setting a limit at 95% CL of 12.2 (observed: 7.8) times the SM cross-section for $M_H = 115\,\mathrm{GeV}/c^2$.

The second analysis extends the data acceptance by allowing looser lepton definitions and increases the jet energy resolution by training a specific NN with the help of several kinematic variables to correct the jet energies from detector effects. The final discriminant is in this case provided by a 2-dimensional NN which separates simultaneously the signal from the Z+jets and the $t\bar{t}$ backgrounds. The result is given by the limits of 9.9 (observed: 7.1) times the SM Higgs cross-section at 95% CL for the $115\,\mathrm{GeV}/c^2$ Higgs.

4. – High-mass Higgs

The Higgs high-mass channel makes use of all the Higgs production mechanisms: $gg \to H$, $q\bar{q} \to WH$, $q\bar{q} \to q\bar{q}H$ (VBF). The allowed final states include WW, VWW, ZWW, WWjj which are triggered searching for a high-energy central muon or electron. The events are further required to include $\not{E}_T$ and a second identified and isolated lepton. The analysis distinguishes between two leptons in the final state having opposite sign (OS) or having the same sign (SS). The whole analysis uses the higher data sample to date in CDF, $3.6\,\mathrm{fb}^{-1}$ and returns a combined result of a limit on the Higgs production of 1.5 (observed: 1.4) times the SM cross-section at 95 % CL for the mass $H = 160\,\mathrm{GeV}/c^2$.

4·1. *Opposite sign*. – In this case, the leptons are coming from the two Ws originated by the H decay and hence forced to have a different sign. The OS branch of the analysis is further divided in subchannels depending on the number of jets present in the final state.

0-jets happens when both the Ws have a leptonic decay and the Higgs comes from gluon fusion ($gg \to H \to WW \to \ell^{\pm}\nu\ell^{\mp}\nu$). In this case the analysis uses ME to build likelihood ratios whose expressions enter a NN which separates the signal from the dominant backgrounds (diboson, W+jets).

In the 1-jet and 2 or more jets channels, all the production mechanisms are allowed and 8 kinematic variables are directly used as inputs for a NN. The main backgrounds are WW production, Drell Yan, W+jets events, $t\bar{t}$.

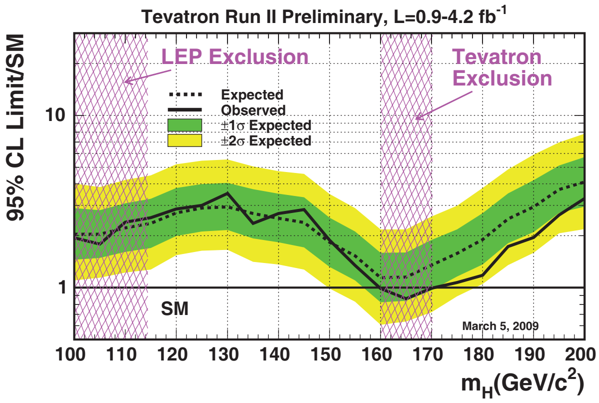

Fig. 2. – Tevatron combined limits on the Standard Model Higgs production cross-section.

4˙2. *Same sign.* – The two leptons are allowed to have the same sign because one comes from the W which gave the Higgs-strahlung, and the second from the Higgs decay. Contributions to this channels are given by ZH and WH produced events. After discriminating the signal and background contributions in the SS channel with a NN trained on 13 variables, a limit (same units as above) of 7.31 (observed: 6.61) is set for this subchannel at $H = 160\,\mathrm{GeV}/c^2$.

5. – Combination

The CDF analyses are combined together in a single limit set where the Higgs mass ranges from 100 to $200\,\mathrm{GeV}/c^2$. Figure 1 shows the individual limits set in each channel studied by CDF and their combination (solid red). An expected limit measures the actual power of an analysis with that specific technique and that amount of data. The observed limit shows the actual limit obtained with the available data.

Figure 2 shows the combination of the CDF limits and the D0 ones. Systematic uncertainties are included in the limit as nuisance parameters while computing the likelihood function [1]. The observed combined limits are lower than the SM Higgs production cross-section, meaning that at 95% CL Tevatron was able to exclude a Higgs boson in the mass window [160; 170] GeV. That is an extremely important result because for the first time some new limit was added to the one found by LEP ($M_H > 114\,\mathrm{GeV}$ at 95% CL).

REFERENCES

[1] CDF Collaboration and D0 Collaboration, *Combined CDF and DZero Upper Limits on Standard Model Higgs-Boson Production with up to* $4.2\,\mathrm{fb}^{-1}$ *of Data*, arXiv:0903.4001 [hep-ex].